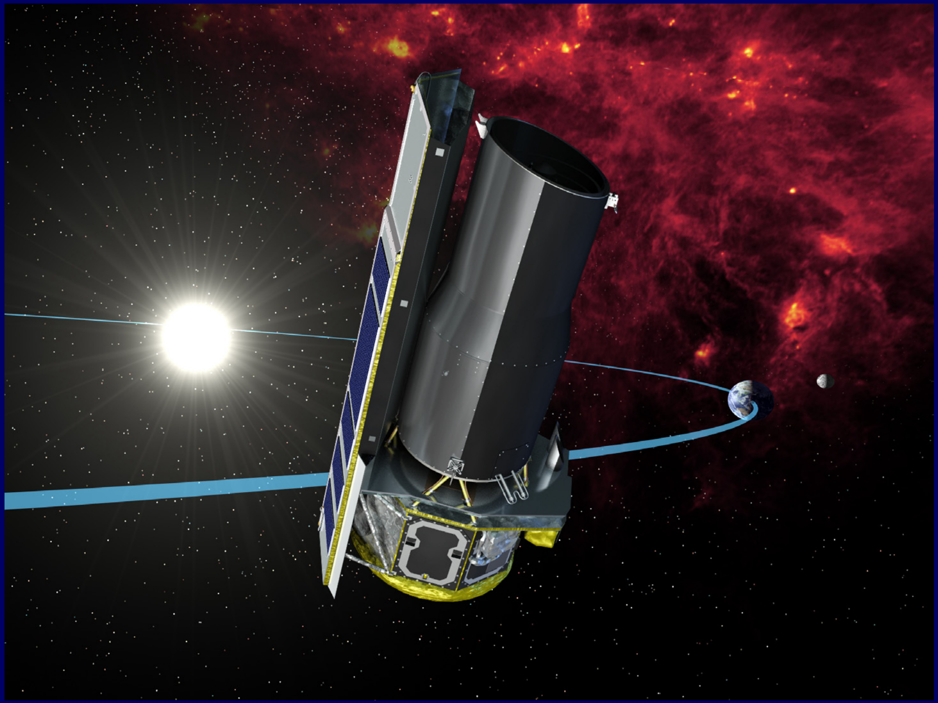


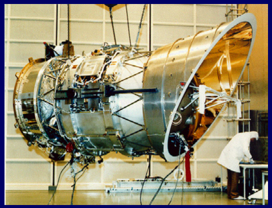
Photoconductors: Spitzer and Beyond

Erick Young
Steward Observatory
University of Arizona

Use of Ge Photoconductors

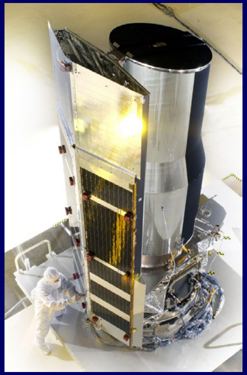
Airborne

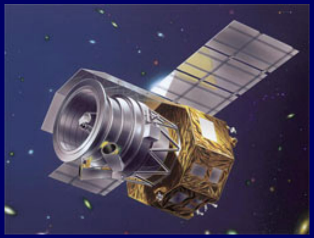
- CGS
- FIFI
- FIFI-LS



Space Experiments

- IRAS
- Spacelab IRT
- COBE
- **ISO - ISOPHOT, LWS, & SWS**
- IRTS
- **Spitzer**
- ASTRO-F
- Herschel – PACS
- Spica





Why Photoconductors?

- System-level advantages of photoconductors
  - Photoconductors reach useful performance levels without sub-Kelvin cooling
    - NEP's of 10^{-18} W $Hz^{-1/2}$ are attained in real systems
  - Photoconductors produce large signals which allow interfacing with cryogenic electronics
  - Photoconductors can be made arrays

Representative Extrinsic Impurities

	Si		Ge	
Impurity	λ_c (μm)	σ_i (cm^{-2})	λ_c (μm)	σ_i (cm^{-2})
Be	8.3	5.0×10^{-18}	52	1.0×10^{-14}
Ga	17	5.0×10^{-16}	115	1.0×10^{-14}
P	27	1.7×10^{-16}	103	1.5×10^{-14}
Sb	29	6.2×10^{-16}	130	1.6×10^{-14}

Special Considerations for Germanium

- Low Photoionization Cross Section
  - Absorption Coefficient a(l) given by:

    $$a(\lambda) = \sigma_i(\lambda)\ N_I$$
  - Maximum doping level limited by onset of impurity hopping

    $$N_I < 2 \times 10^{14}\ cm^3$$
  - Detectors must be physically large for adequate absorption
    - Alternative approach is to place detectors in an integrating cavity
- Low Detector Bias Operation
  - Typical detector biases are less than 100 mV
  - Ge detectors are sensitive to amplifier instabilities
- Low Temperature Operation
  - Typical temperatures are less than 2 K
    - Exacerbates many non-ideal behaviors

Ge:Ga Typical Parameters

Acceptor Concentration	2×10^{14} cm^{-3}
Donor Concentration	$< 1 \times 10^{11}$ cm^{-3}
Typical Bias Voltage	50 mV / mm
Operating Temperature	< 1.8 K
Responsivity	7 A/W
Quantum Efficiency	20%
Dark Current	< 180 e/s

Stressed Detectors

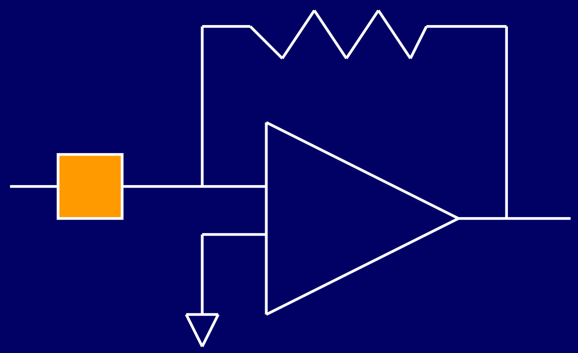
- Photoconductivity in P-type detectors is caused by the migration of holes in the crystal
- By applying stress on the [100] crystal axis, it is possible to reduce the hole binding energy and consequently increase the wavelength response of the detector
  - Example: Ge:Ga

    Application of 500 N force on a 1 mm cube of Ge:Ga, the cutoff wavelength can be extended beyond 200 μm

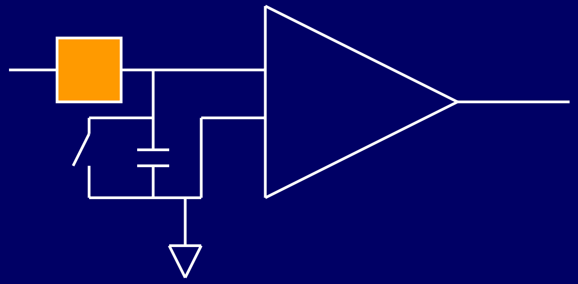
    Used on ISOPHOT, ISO LWS, IRTS, SIRTF MIPS, and ASTRO-F

Readout Considerations

- Transimpedance Amplifier
  - Used on IRAS
  - Maintains Detector Bias
  - Subject to Thermal Noise of Feedback Resistor

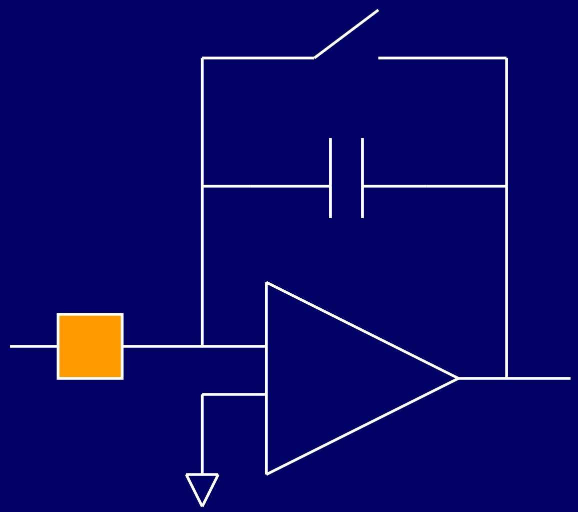


- Integrating Amplifier
  - Used on SWS and LWS
  - Avoids Thermal Noise
  - Detector debiases during observation



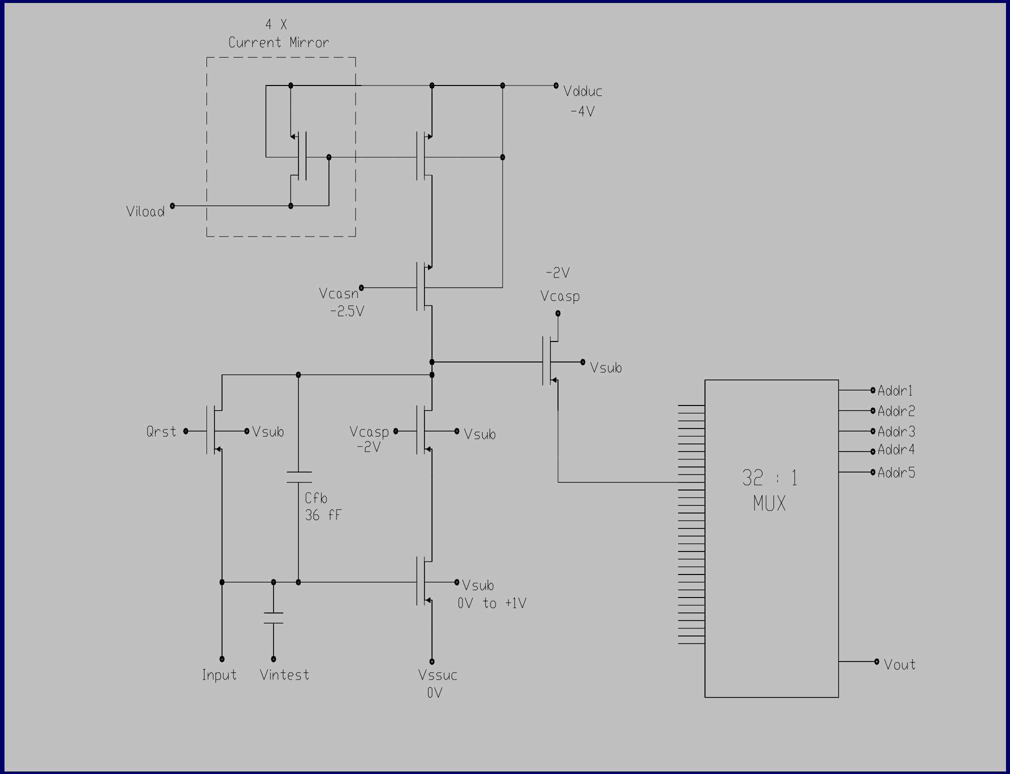
Readout Considerations

- Capacitive Transimpedance Amplifier
  - Used on ISOPHOT , MIPS, and ASTRO-F
  - Avoids thermal noise of feedback resistor
  - Maintains detector bias
  - Provides gain with appropriate choice of feedback capacitor
  - Zero electronic crosstalk
  - Requires DC stable amplifier for proper operation

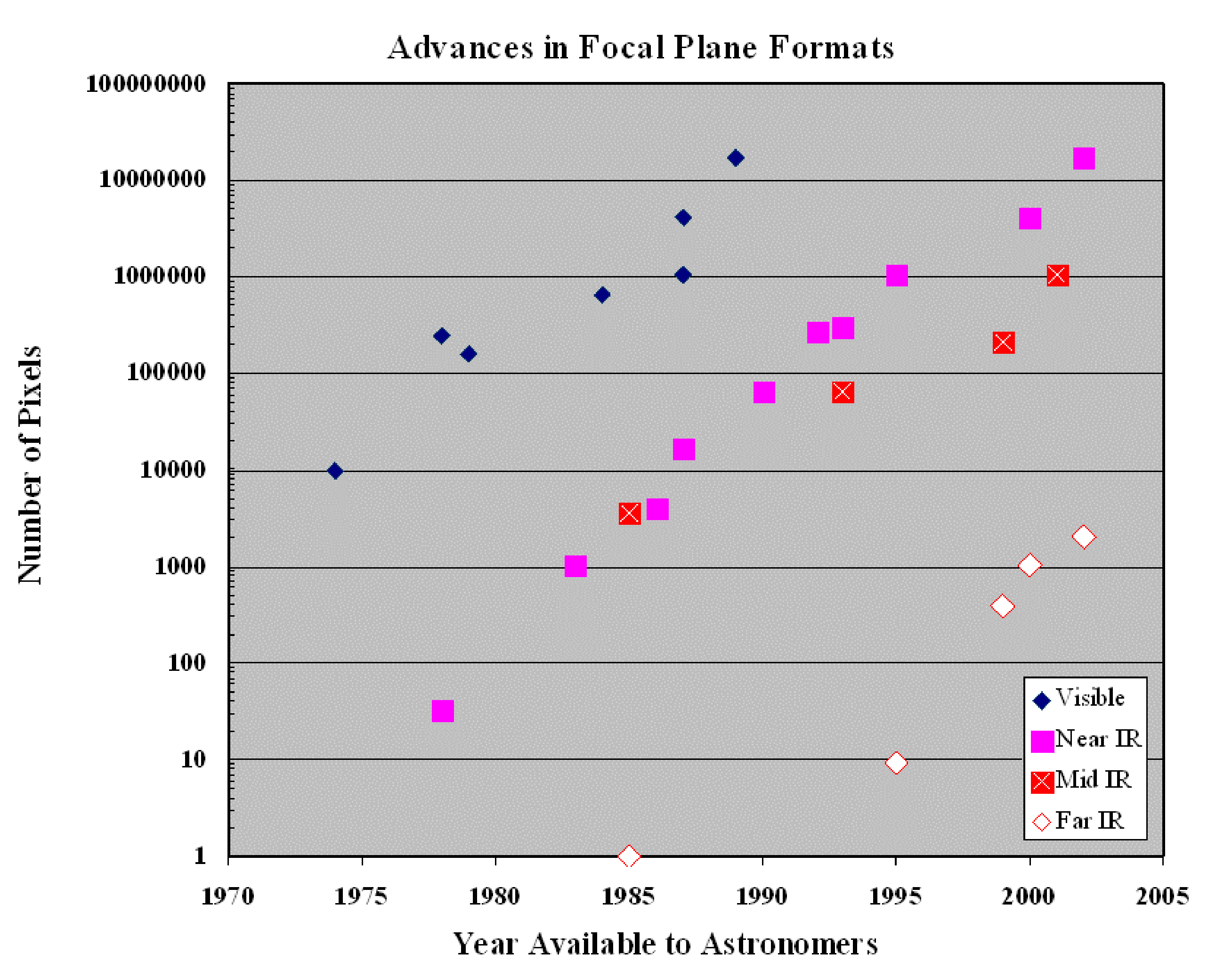


Spitzer Readout Development

- Germanium Photoconductors Low Bias Voltage Devices
- Typical Switched FET Amplifiers Produce Large Voltage Transients
  - Use CTIA circuit
- Requirement: DC Stable Amplifier
  - Operation at 2 K, well below silicon freezeout (20K)
  - CRC-696 Devices (Raytheon)
    - Degenerately-doped substrate
    - Very thin, lightly -doped epitaxial layer
    - Highly doped contacts
    - 32-channels



Infrared Moore's Law



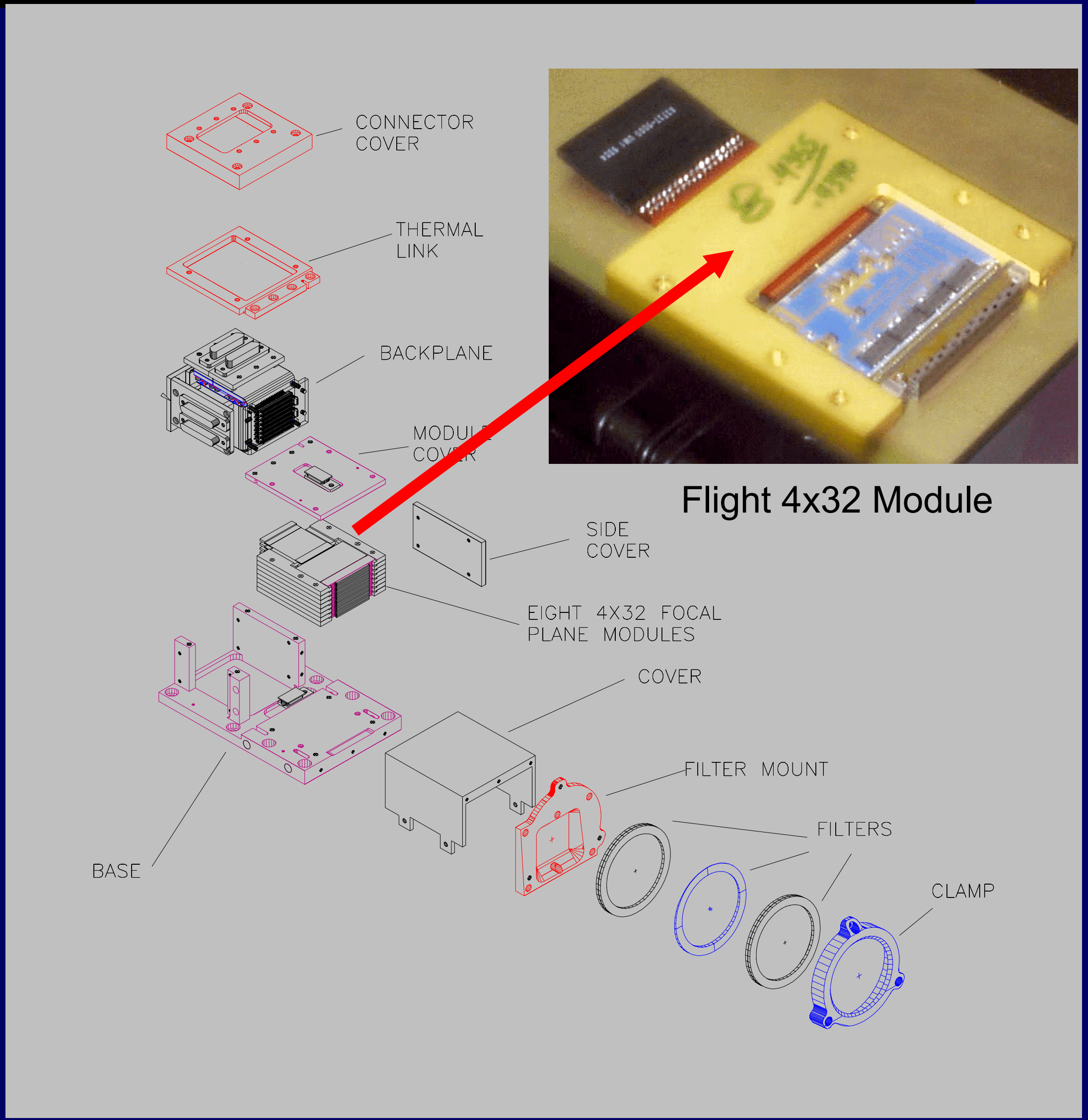
MIPS 70 µm Array

32 x 32 Ge:Ga photoconductor array

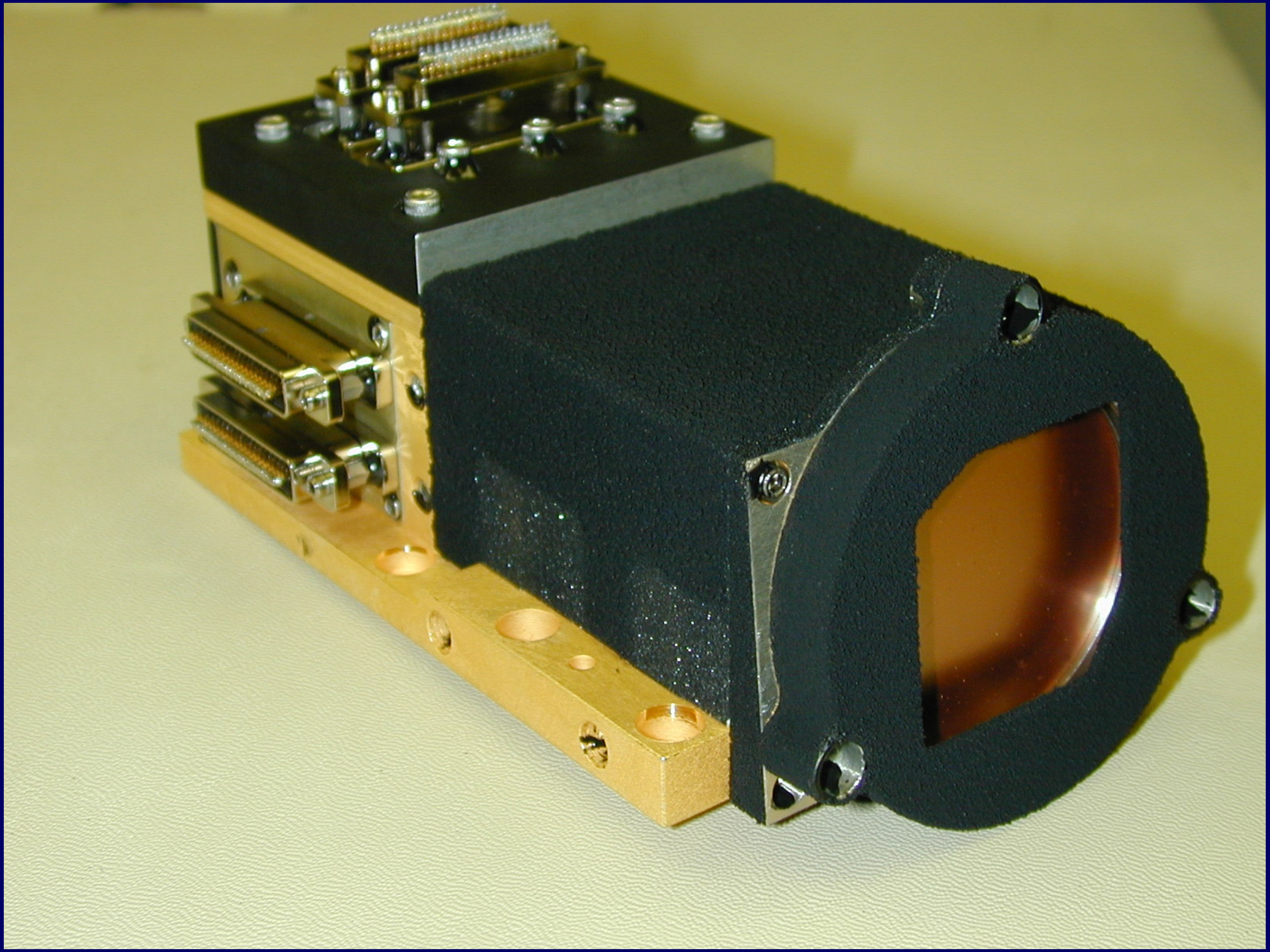
Developed and constructed at Steward Observatory

Detector material from Lawrence Berkeley Laboratory

Custom cryogenic readouts (CRC-696)



Flight 70 μm Array



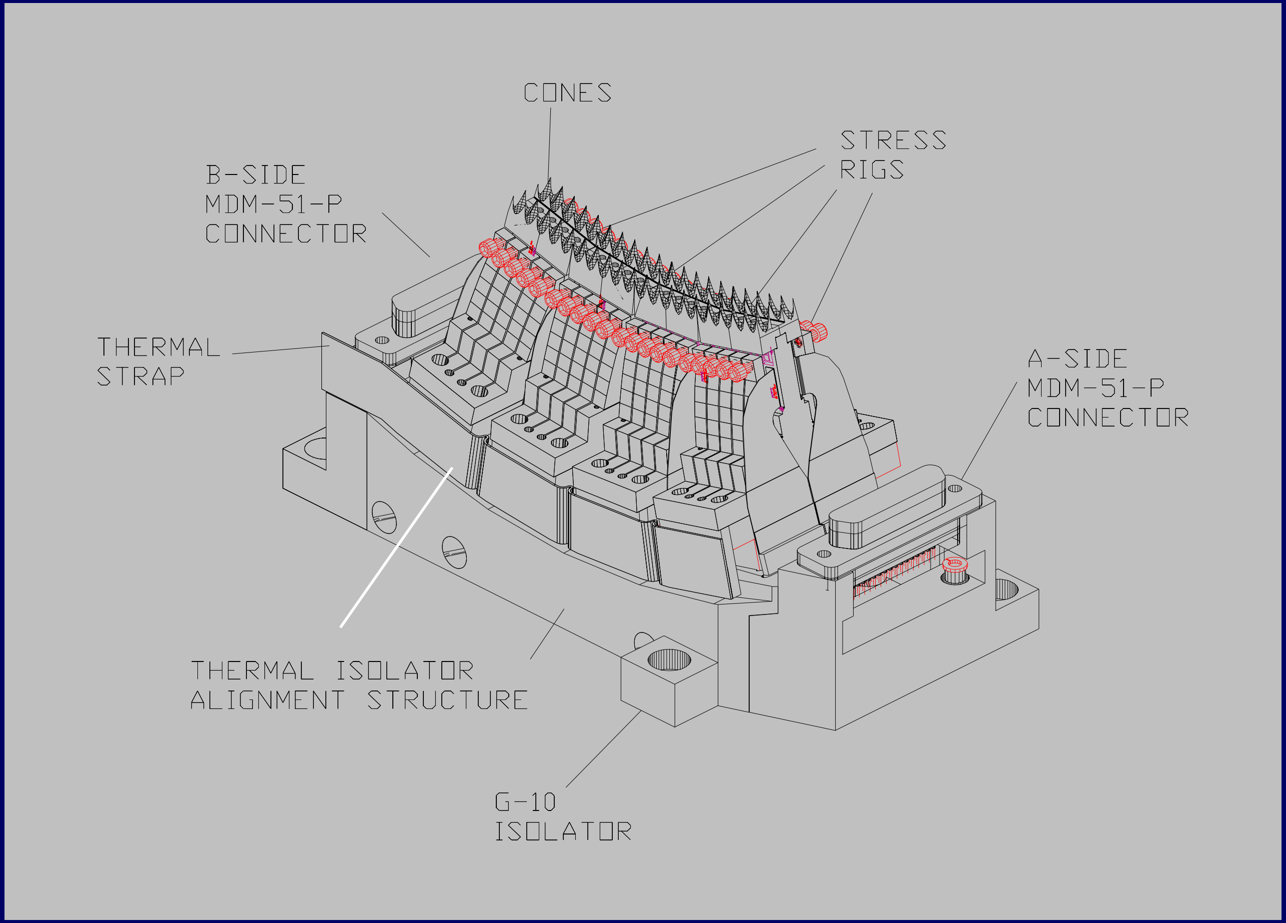
MIPS 160 μm Array

2 x 20 Stressed Ge:Ga photoconductor array

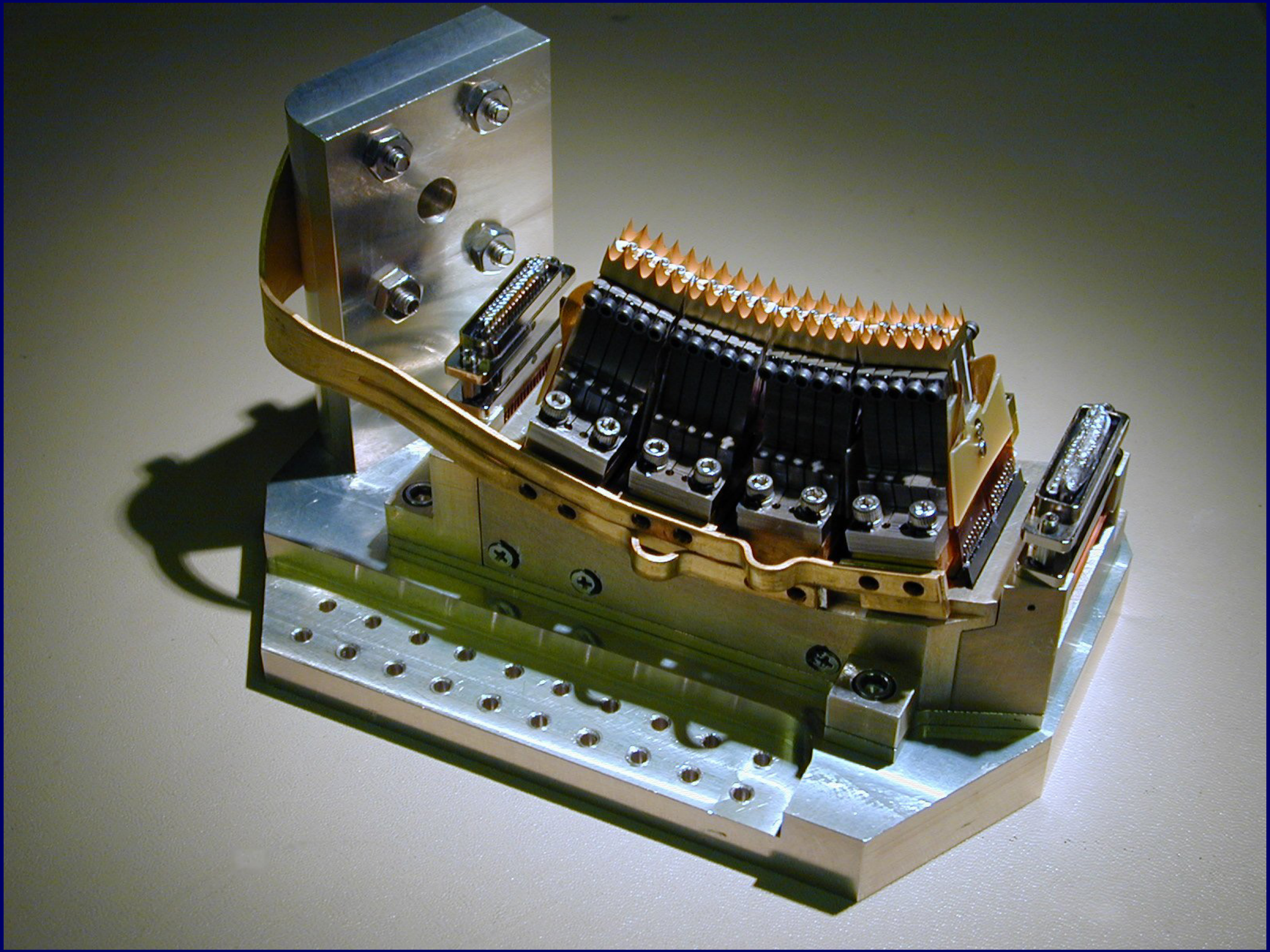
Developed and constructed at Steward Observatory

Detector material from Lawrence Berkeley Laboratory

Custom cryogenic readouts (CRC-696)



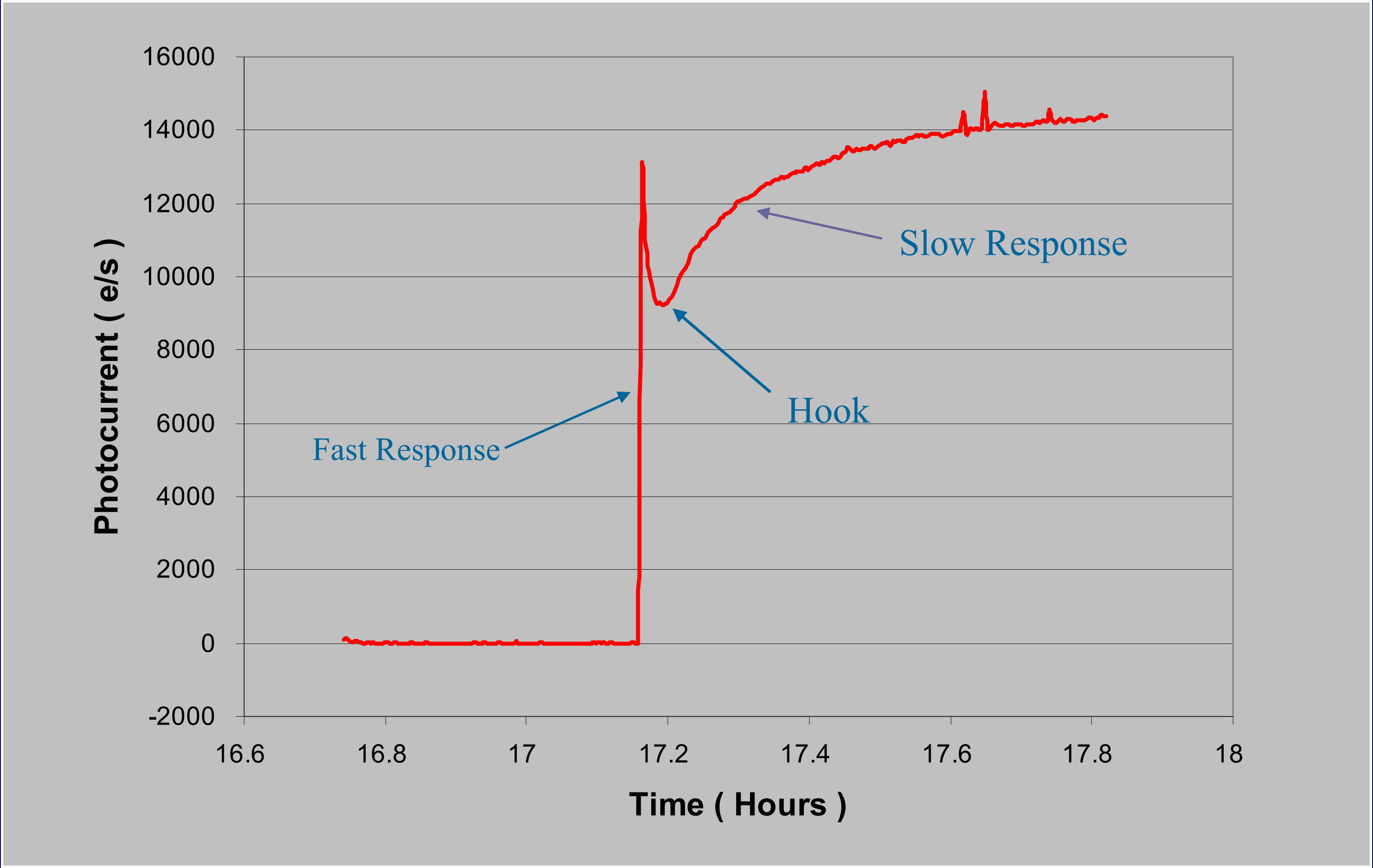
Flight Stress Detector Array



Photoconductor Non-Ideal Response

- Nonlinear Response
  - Hook Effect
  - Dielectric Relaxation
  - Background Dependent Responsivity
- Ionizing Radiation Response
  - Increase in Responsivity with Exposure
    - Up to 10x increase
    - Background dependent
    - Slow Recovery with Low Backgrounds
    - Remediation
      - Thermal Anneal
      - Bias Boost
      - Photon Flood
  - Glitches

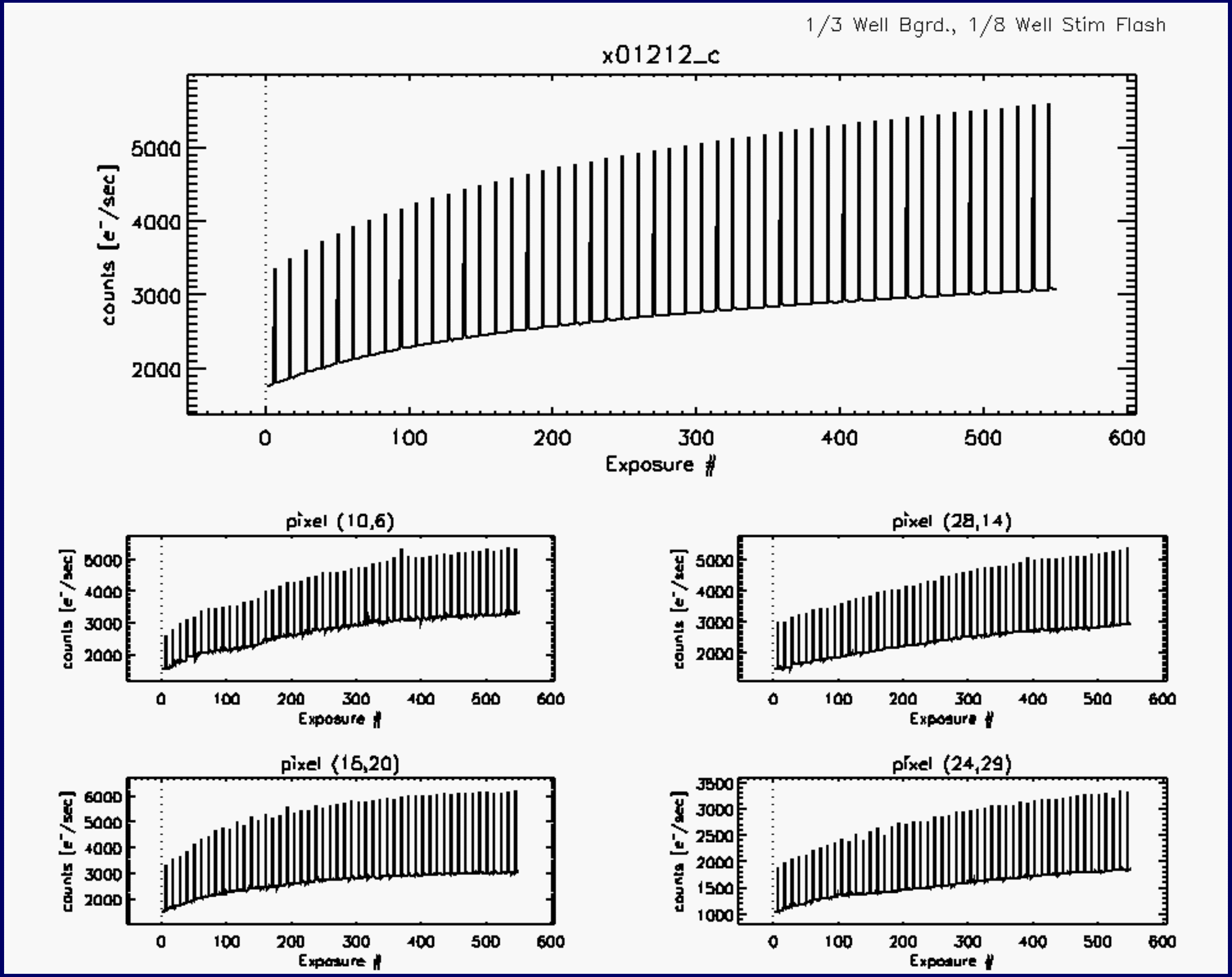
Ge:Ga Transient Response



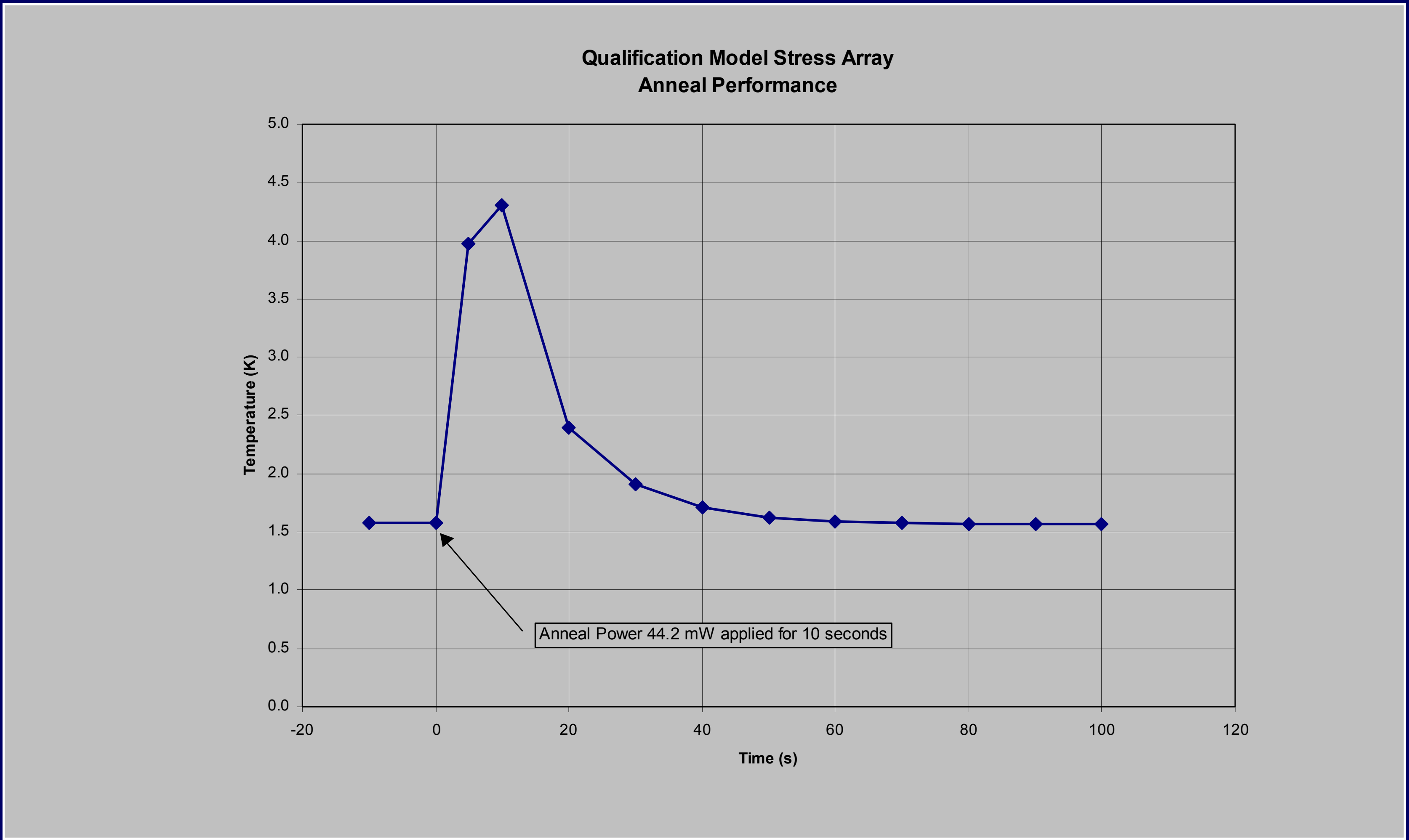
Ge:Ga Responsivity Change

- Example of Response to Ionizing Radiation
  - Am^{241} γ-Rays
  - Zilch Background
- Increase in Responsivity
  - Background Dependent
  - Slow Recovery Times
- Except for event amplitudes, behavior is similar with protons

Use Stimulators with MIPS Instrument



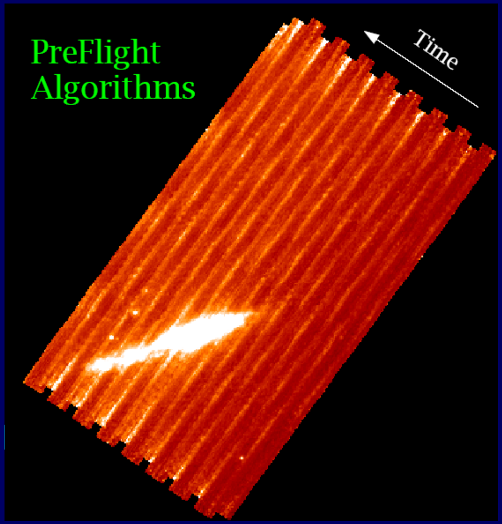
Anneal Test

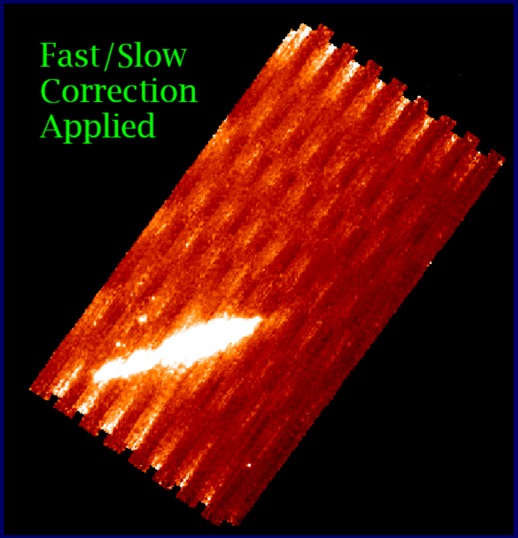


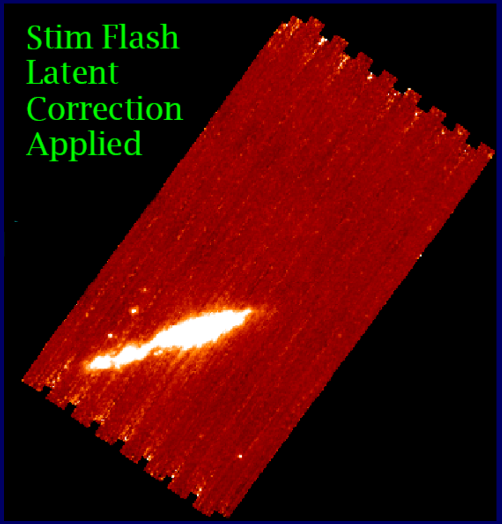
Qualification Model Stress Array
Anneal Performance
Temperature (K)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-20
0
20
40
60
80
100
120
Time (s)
Anneal Power 44.2 mW applied for 10 seconds

Improvements in Algorithms

Observations of dwarf galaxy NGC 55 demonstrate improvements in MIPS pipeline incorporating knowledge of on-orbit effects.

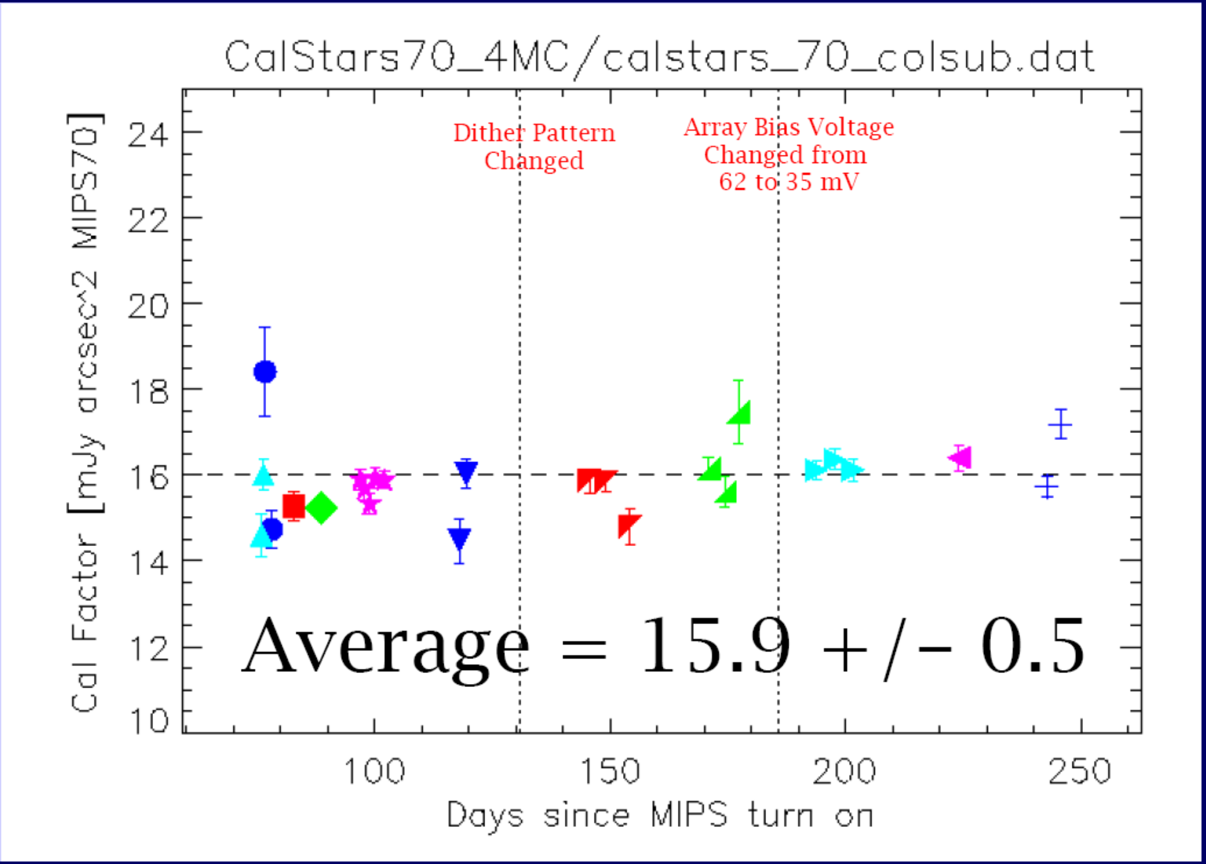






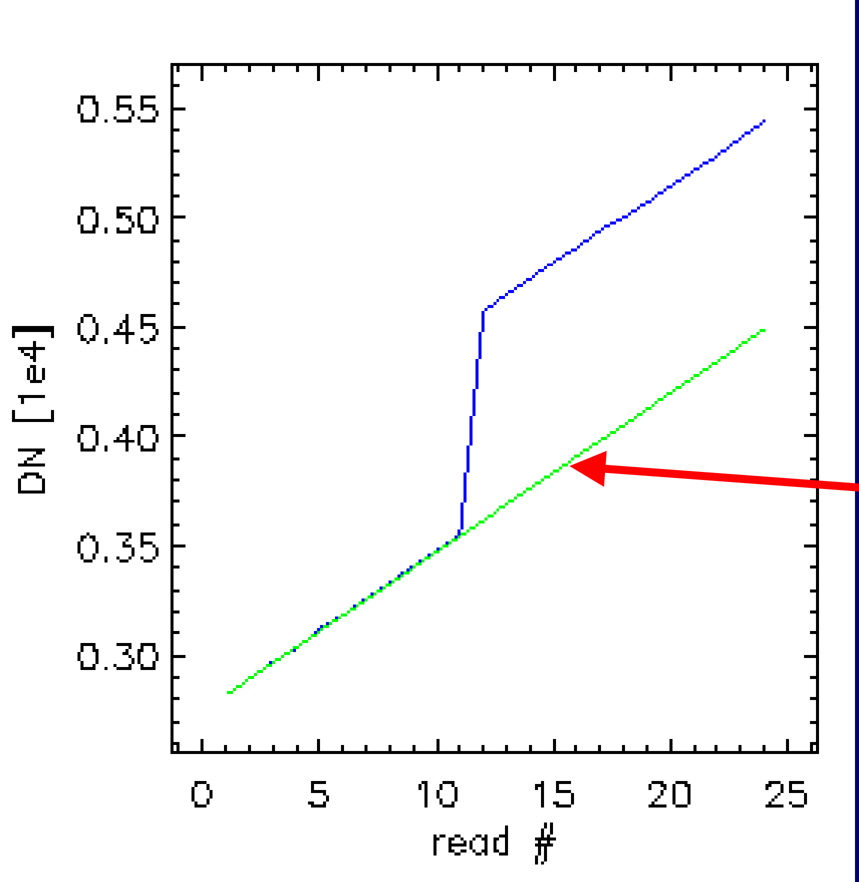
Engelbracht et al. 2004

Standard Star Repeatability



- Standard Star HD 163588 is observed multiple times each MIPS campaign in photometry mode.
- Flux is 325 mJy.
- Repeatability over the first half year is 3%.
- Use of stimulators and thermal anneals works!

Ge:Ga Response to Cosmic Rays

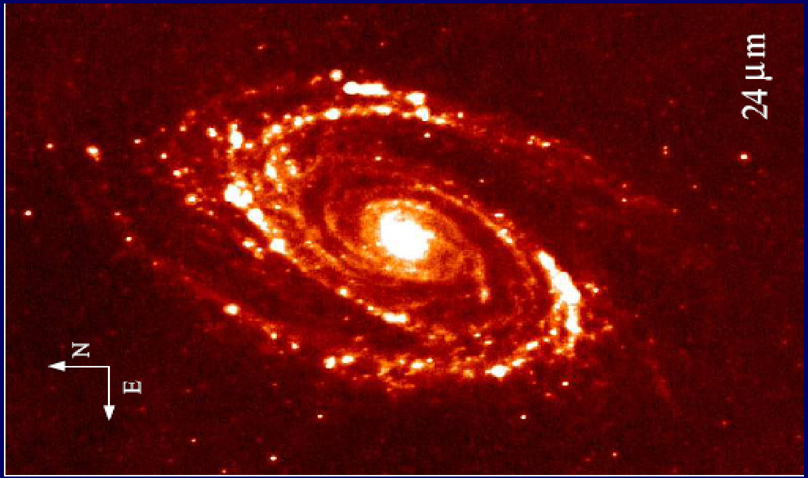


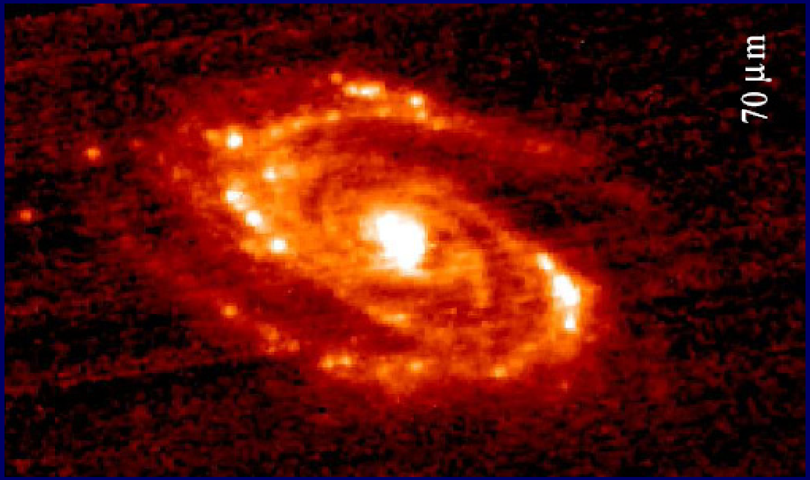
- Typical cosmic ray hit
  - Detector is usually well behaved after hit
  - DAT identifies events and fits slope to pre-hit part of ramp

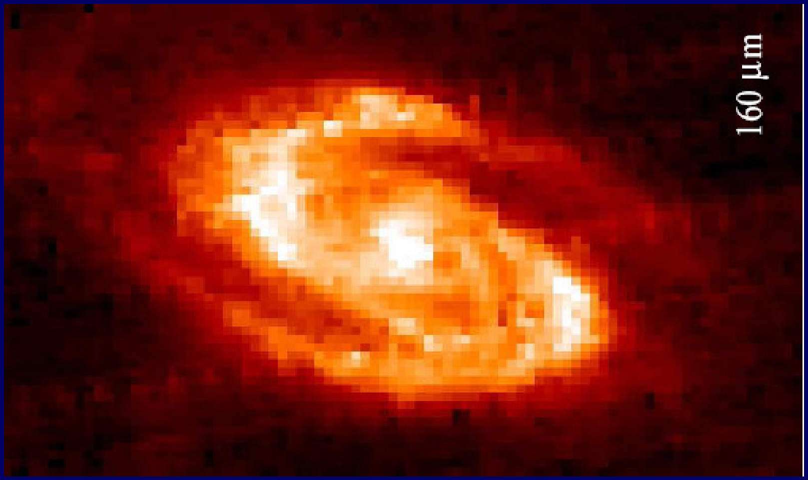
Performance Summary

- MIPS 24 μm Array
  - Performance is excellent: about 2x more sensitive than predicted
  - Photometric repeatability better than 1%
  - Point source sensitivity is 0.11 mJy, 5-σ, 500 seconds.
  - Reaches the confusion limit in 1900 s.
- MIPS 70 μm Array
  - Detectors are reasonably well behaved
  - Uncorrected radiation effects result in ~2x degradation to pre-launch predictions
  - Cryostat cable problem introduces excess noise in half the array
  - Point source sensitivity is 6 mJy, 5-σ, 500 seconds on good side
  - Reaches confusion limit in about 1800 s.
- MIPS 160 μm Array
  - Overall performance is good
  - Short wavelength stray light path results in spectral leak at 10^{-4} level
  - Point source sensitivity is 15 mJy, 5-σ, 500 seconds
  - Reaches confusion limit in a few hundred seconds.

MIPS M 81 Montage

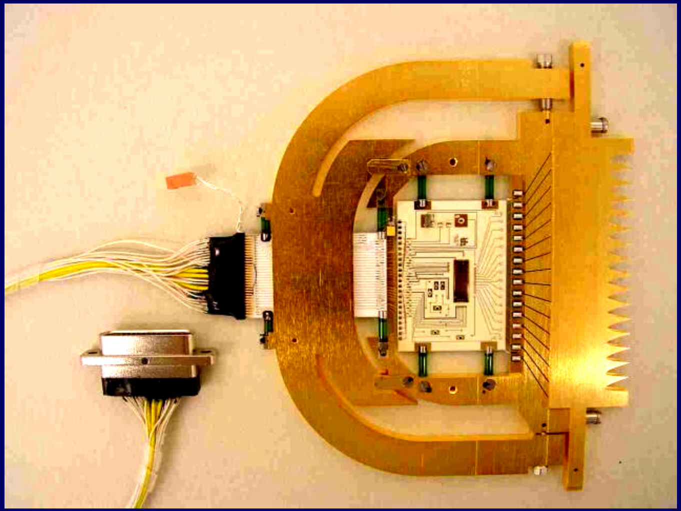


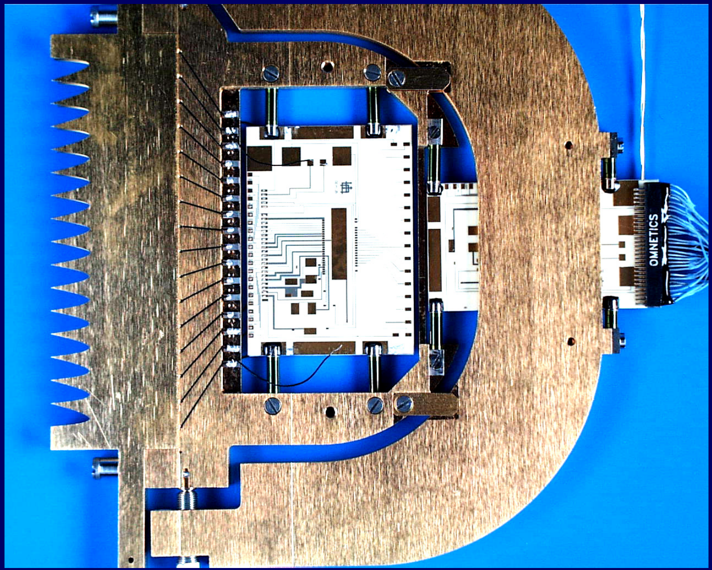




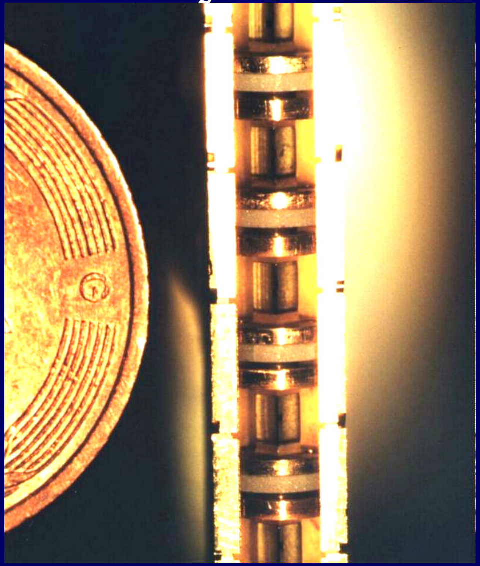
Gordon et al (2004)

PACS Array Design

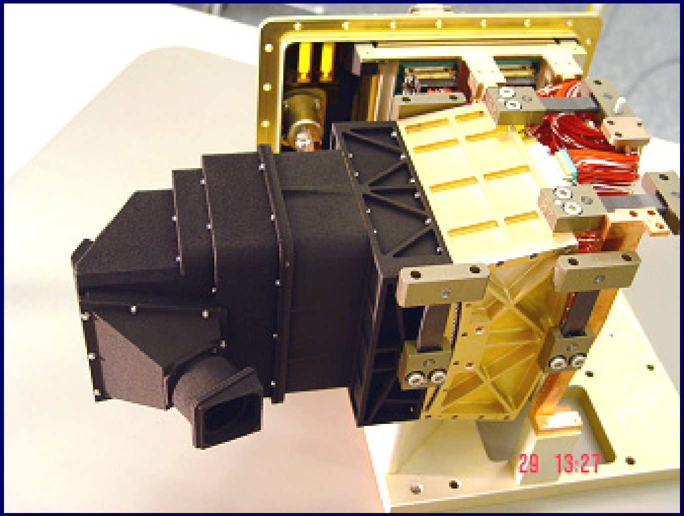




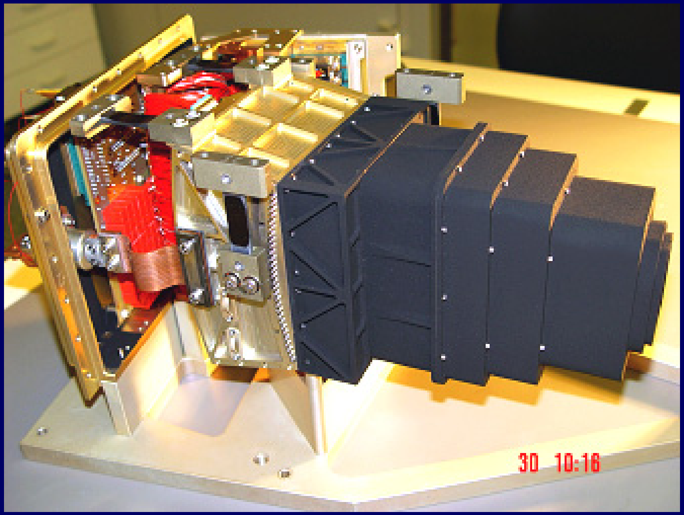
- design for red and blue array identical except for softer clamp for blue array
- maximum stress:
  blue array 200 N/mm^2
  red array 800 N/mm^2



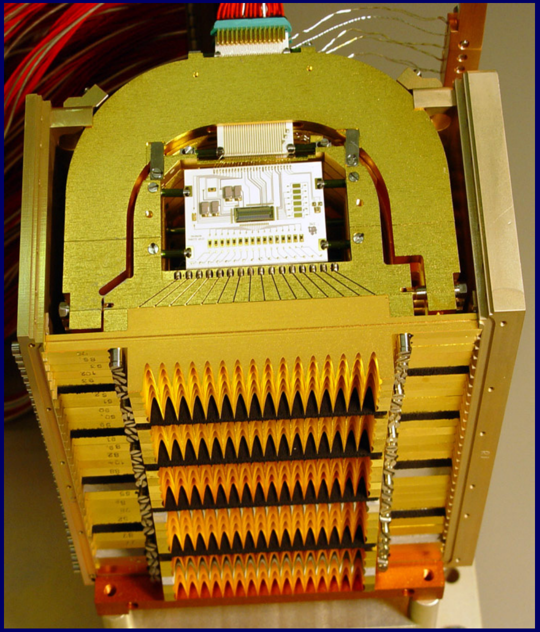
PACS Arrays



Red Array



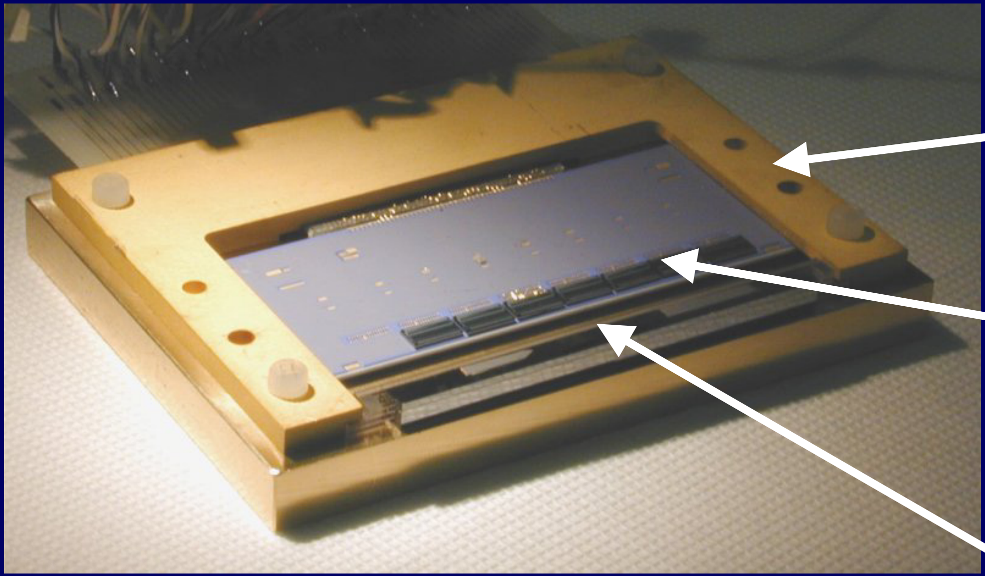
Blue Array



Future Needs

- Bigger Arrays
  - $\lambda/2D$ for SAFIR is 0.7” at 70 μm
  - To cover even modest fields of 1 – 2 arcmin will require arrays of 128x128 or even 256x256 pixels
- Extended Wavelength Response
  - Stressed detectors will be prohibitively difficult in desired formats.
- Better Arrays
  - There is a need for higher sensitivity, especially in spectroscopic applications. NEP’s as low as 10^{-20} $WHz^{-1/2}$ will be needed

Extension of MIPS Architecture

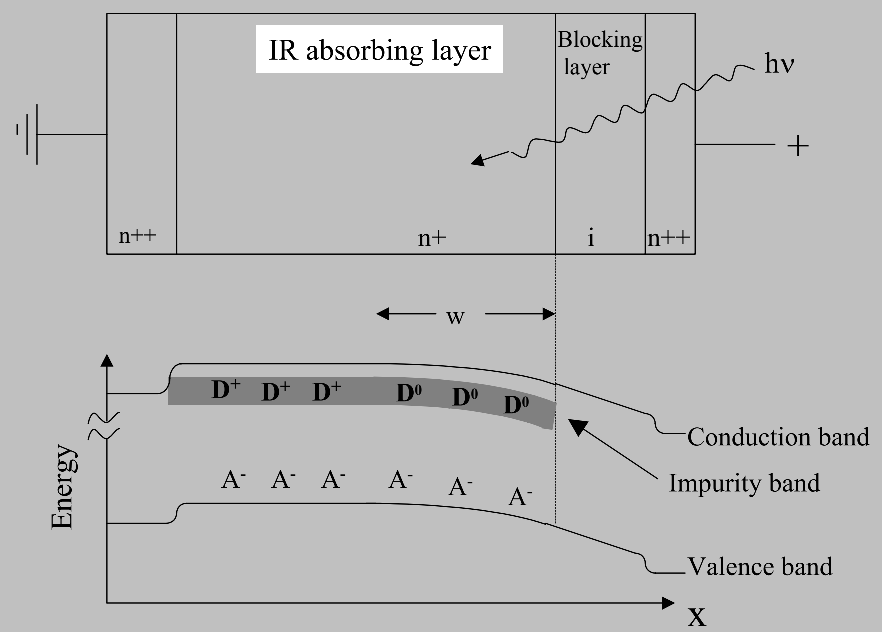


- 4x64 Building Block
- Leads to 64x64 array
- Molybdenum Frame
- SBRC-190 Readouts
  - Selectable feedback capacitors up to 7 pF
- Ge:Ga Photoconductors

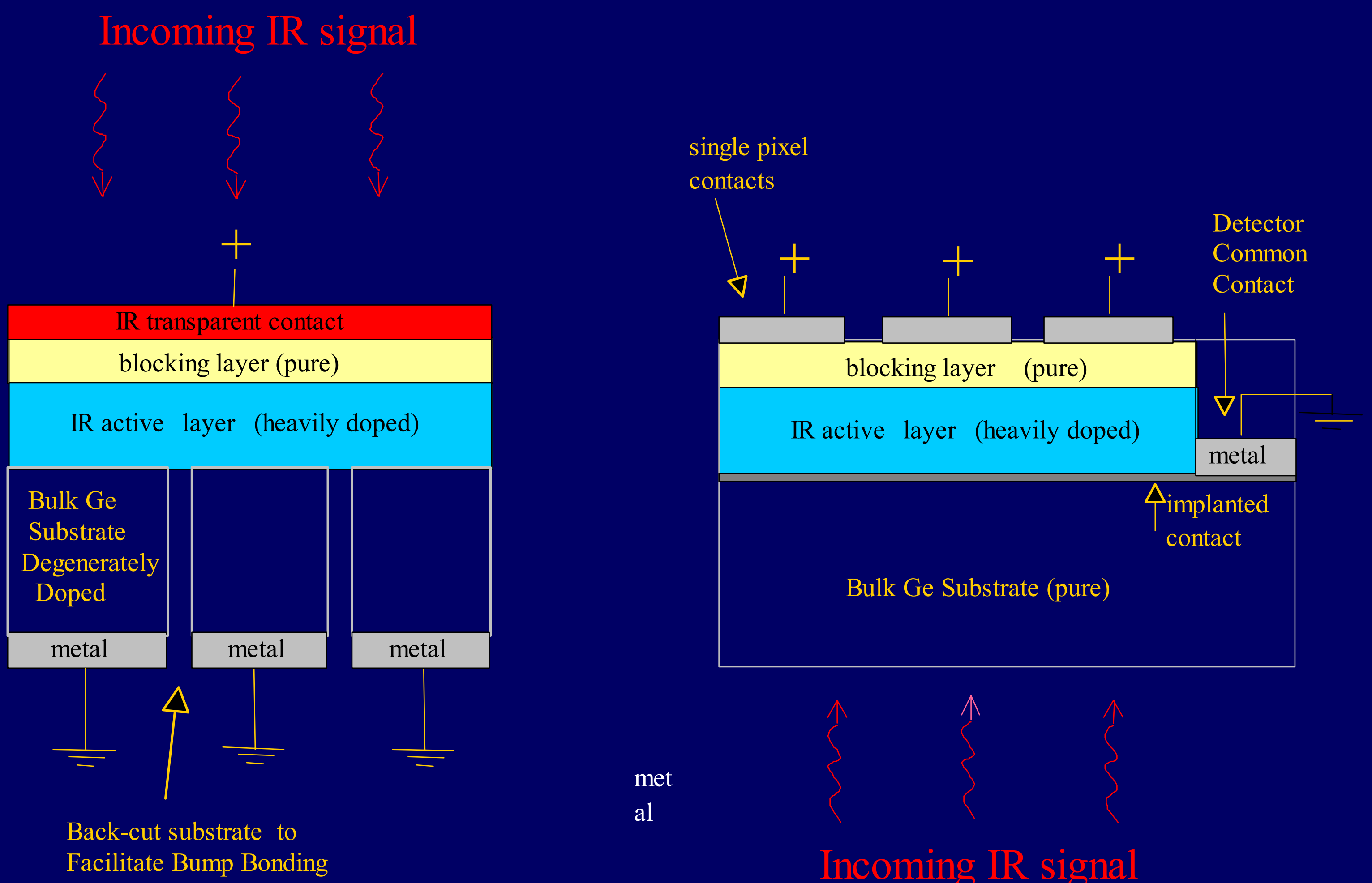
Impurity Band Conduction Detectors

- IBC Detectors Address Many of the Problems of Conventional Photoconductors
  - Nonlinear Response
  - Radiation Sensitivity
    - Low Volume Cross Section
    - High Acceptor Concentration
- Efforts to Date
  - Ge:Ga IBC Detectors (LBNL, Rochester)
  - GaAs IBC Detectors (LBNL, MPE, MPIF)
- Issues
  - Blocking Layer Purity
  - Passivation
  - Blocking Layer Thickness

BIB Band Diagram

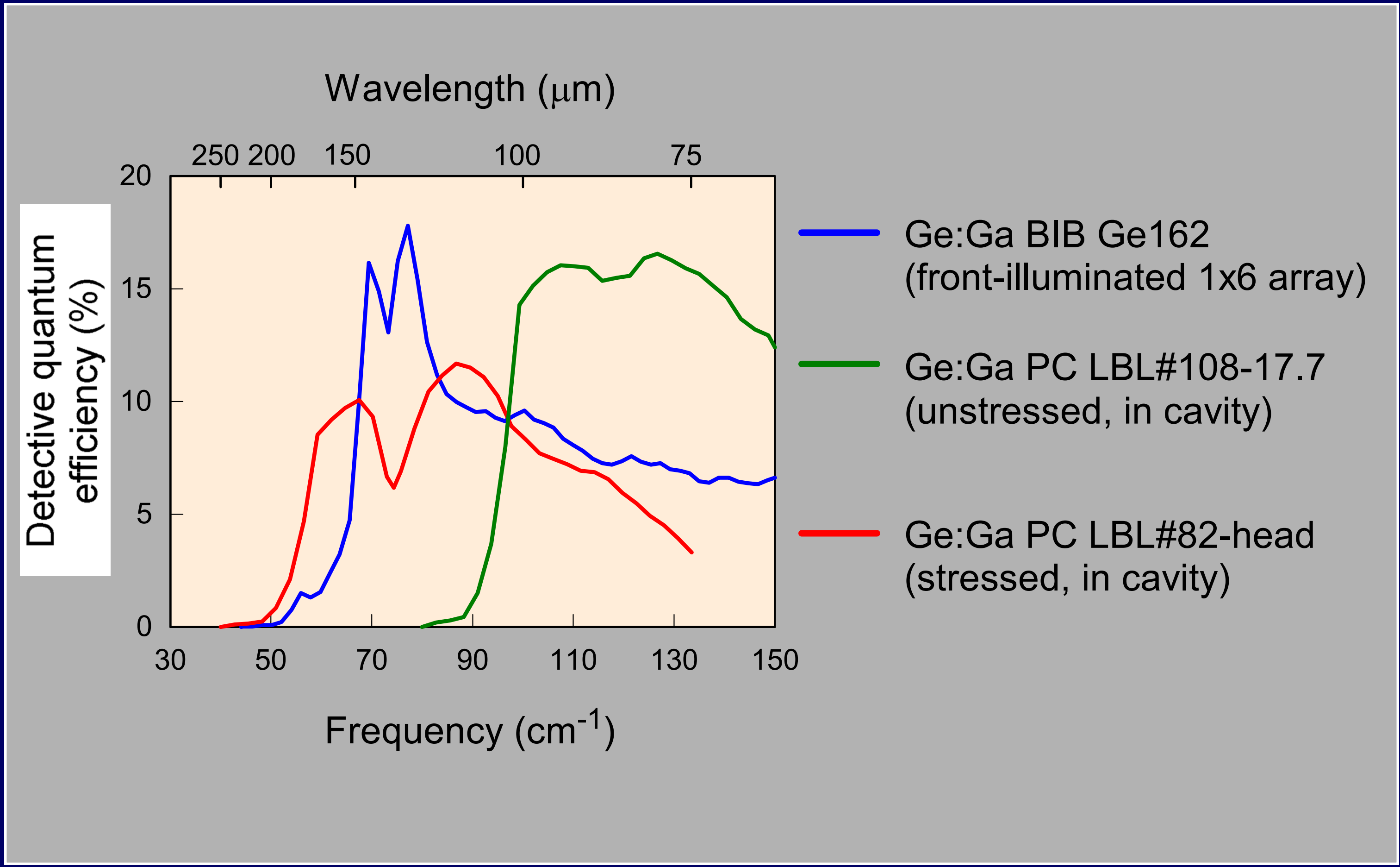


Blocked Impurity Band Detectors



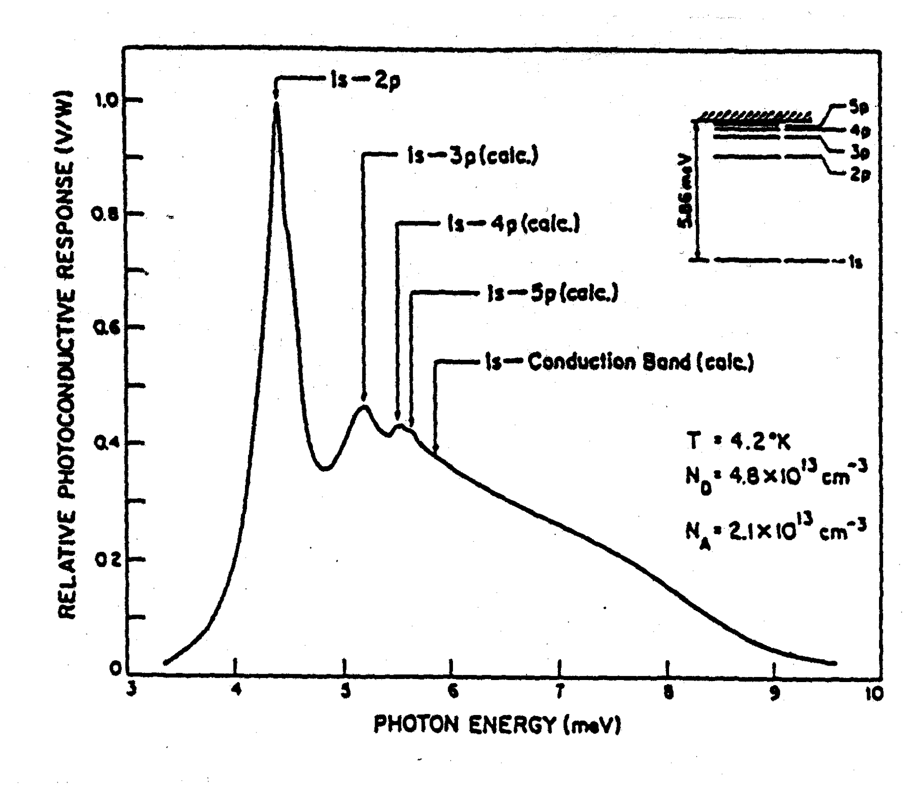
Thanks to Eugene Haller & Jeff Beeman

Comparison of Ge BIB with Ge PC

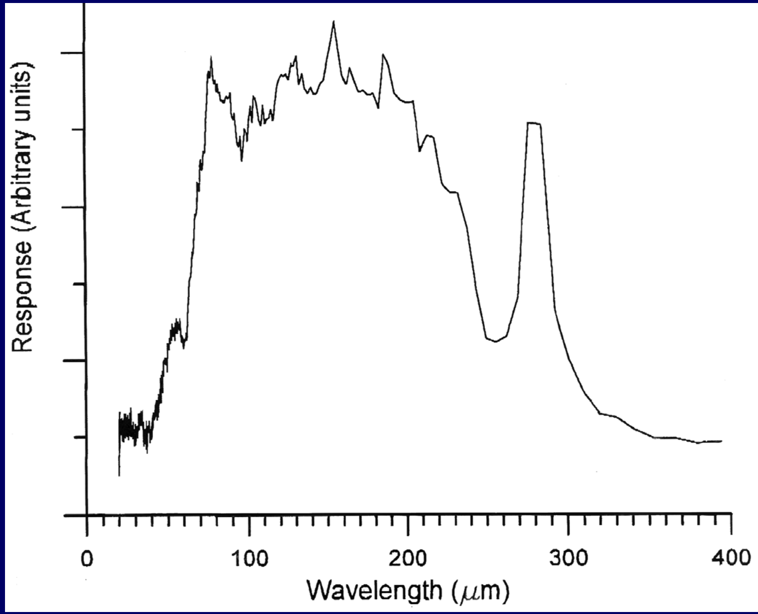


Dan Watson (1996)

Measured Spectral Response for n-type GaAs

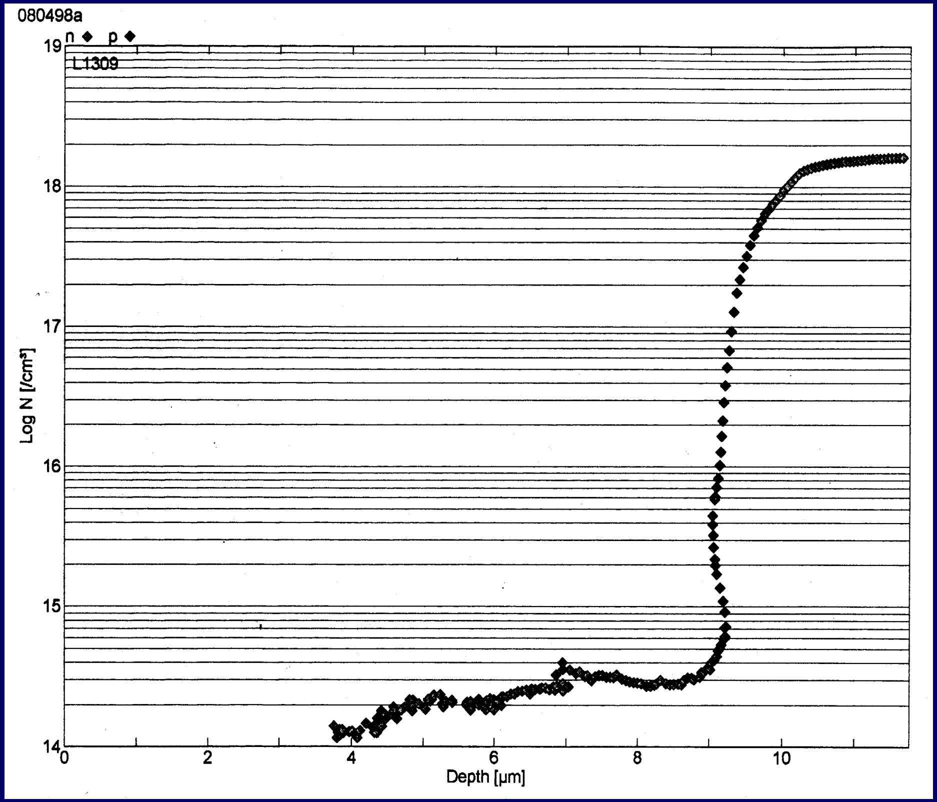


Stillman et al. 1977



MPE / MPIF / LBNL 1999

Experimental results achieved so far



- Blocking layer interface: Gradient of donor concentration at I/F shows orders of magnitude increase within 1 µm thickness (see diagram)
- Purity achieved in small samples:
  10^{11}-10^{12} cm^{-3} at LBNL
  10^{12}-10^{13} cm^{-3} at MPIF
- Controlled donor doping above 10^{14} cm^{-3} is a proven process step

Summary

- Germanium Far Infrared Detectors have been the Detectors of Choice for Far Infrared Astronomy between 50 - 240 μm
  - Wide use in a large number of flight missions
  - High performance under low backgrounds
  - Large format arrays possible
  - Relatively modest temperature requirements
- Efforts to understand photoconductor non-linear behavior yielding fruit
- Readouts are a key system element
- Efforts to produce far infrared IBC detectors underway